Deformation in the Casa Diablo Geothermal Well Field, Long Valley Caldera, Eastern California

By James F. Howle *and* Christopher D. Farrar

Long Valley Caldera in eastern California has been the site of seismic swarms and deformation in response to magmatic intrusions since 1980 (Hill and others, 1985; Langbein, 1989; Langbein and others, 1993). Magmatic intrusions are causing regional uplift of the land surface across the resurgent dome and the Casa Diablo geothermal well field (figs. 1 and 2). Superimposed on the regional uplift is local subsidence in and around the well field caused by pumping of geothermal fluid. This paper presents a time-series overview of land-surface deformation in the well field and relates the deformation to the two principal sources of stress—magmatic inflation and pumping of geothermal fluid. Leveling data from three networks that overlap areally and temporally are presented beginning with the bench marks along Highway 395.

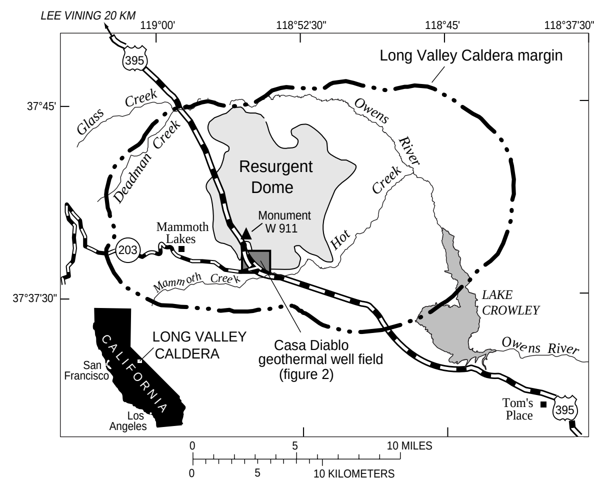

Figure 1. Location of Long Valley Caldera, California.

The Highway 395 long base-line network extends 65 km from Lee Vining to Tom's Place, California. Bench marks are spaced at intervals less than or equal to 1 km. Elevation changes for bench marks in the Highway 395 long base-line network for three periods between 1983 and 1992 are shown in figure 3. Elevation changes for 1983 to 1985 indicate uniform uplift across the well field that totals about 20 mm (Savage and others, 1987; Dan Dzurisin, geologist, U.S. Geological Survey, written commun., 1993). Elevation data for 1983 to 1985 provide a preproduction base line of the land surface and indicate that no significant subsidence occurred before geothermal fluid was pumped.

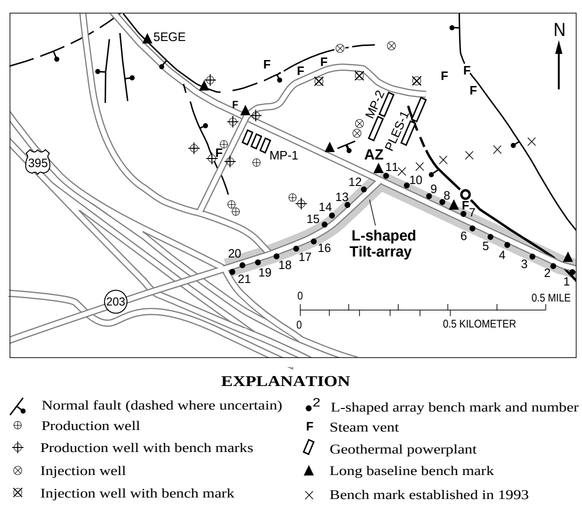

Figure 2. Casa Diablo geothermal well field, monument networks, and bounding normal faults.

Electric-power generation using geothermal fluid in the Casa Diablo field began in 1985 with one powerplant (MP-1) that produced about 10 megawatt gross electric power (Mwe). All of the 0.8×10^6 kg/hr of fluid is pumped from wells and circulated through the MP-1 powerplant and returned to the subsurface through injection wells. Fluid with a temperature of about 170°C is pumped from a 150- to 200-meter-deep production zone and loses about 70°C in the heat-exchange process before it is injected into a zone 600 to 700 m deep.

Between 1985 and 1988, bench-mark elevation changes indicate that monument W911, 2 km north of the well field, moved up about 80 mm in response to regional inflation caused by magmatic intrusions (fig. 3). Monument AZ moved up only about 30 mm, which is equivalent to about 50 mm of local subsidence for that period. In figure 3, elevation change is for a particular period and is not cumulative from 1983. From 1983 to 1992, the cumulative elevation change for monument W911 is about 200 mm. All monuments within about 1 km of monument AZ subsided relative to the regional uplift and clearly define the extent of the localized subsidence caused by pumping of geothermal fluid along the Highway 395 long base line. For 1985 to 1988, subsidence related to geothermal pumping counters but does not entirely mask the regional uplift from magmatic intrusions.

In December 1990, two additional powerplants (MP-2 and PLES-1) became operational. About four times as much geothermal fluid is required to operate all three powerplants as was needed for MP-1 alone. Bench-mark elevation changes on the Highway 395 long base line between 1988 and 1992 (fig. 3) show that W911 was uplifted about 100 mm; however, monument AZ subsided about 20 mm. The increase in pumping from 0.8×10^6 kg/hr to 3.0×10^6 kg/hr caused the local area of subsidence to expand almost 2 km on either side of monument AZ (fig. 3) and completely masked regional uplift of monument AZ and nearby monuments.

The second leveling network is the L-shaped tilt array, a network of closely spaced monuments along two nearly perpendicular lines (fig. 2). Data from this network also show subsidence caused by pumping of geothermal fluids. Differences in monument elevations between consecutive surveys are resolved into north and east components of ground tilt. Data for the north component of tilt for 1984 to 1994 are shown in figure 4. Through 1984, the data show a tilt to the south of 5 μrad/yr in response to magmatic inflation north of the well field. The next leveling of the tilt array in 1985 revealed a reversal in the tilt direction as a result of the onset of geothermal production. Subsequent surveys through 1989 reveal a linear tilt rate of 38±2 μrad/yr to the north toward the well field.

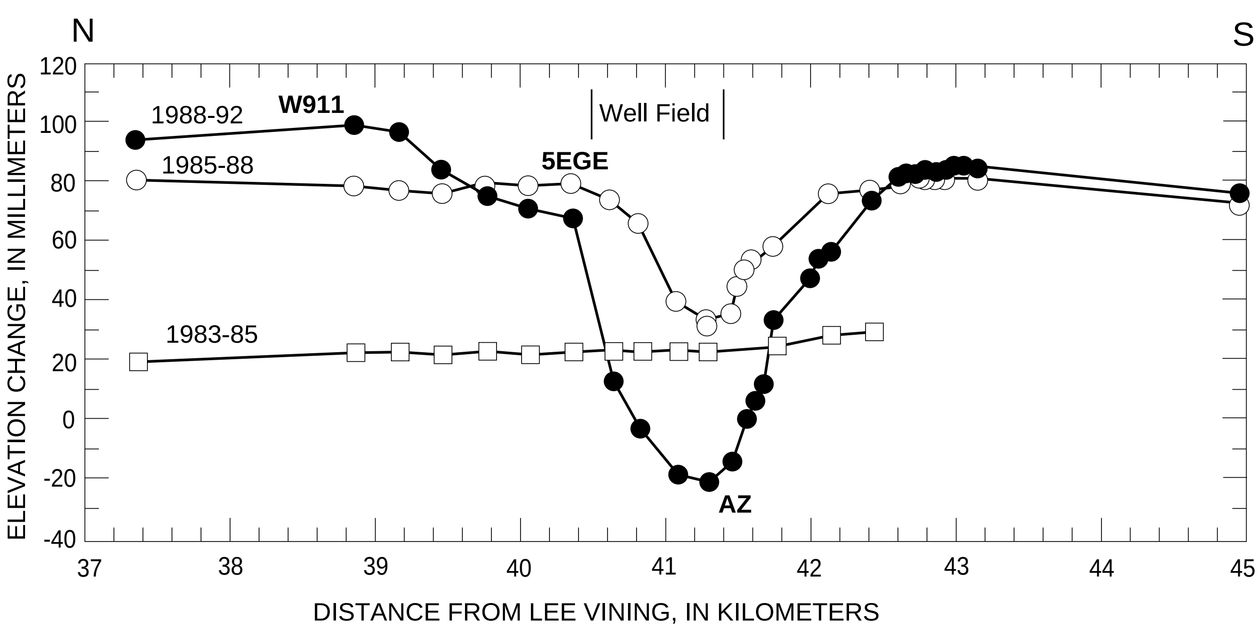

Figure 3. Elevation changes in the Highway 395 long base line for three periods between 1983 and 1992. Elevation change is for an individual period and is not cumulative from 1983 (modified from Sorey and others, 1995).

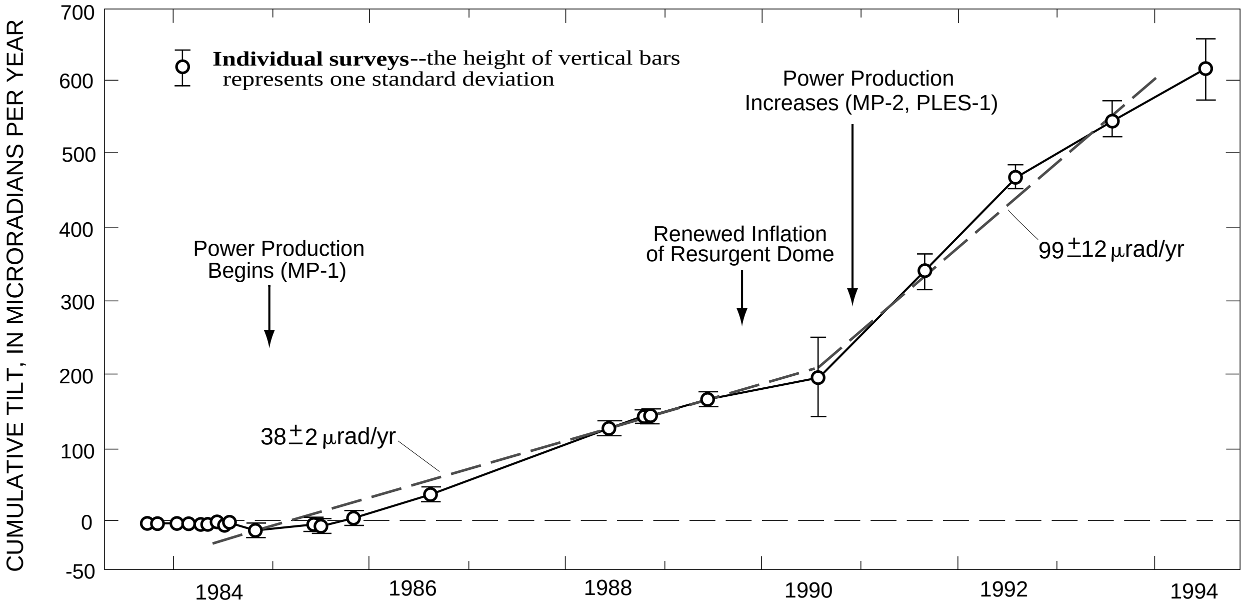

Figure 4. Cumulative land-surface tilt (modified from Sorey and others, 1995).

Renewed inflation of the resurgent dome in late 1989 (Langbein and others, 1993) could be the cause of the slight decrease in tilt observed between the 1989 and 1990 surveys. In December 1990, pumping was increased by 2.2×10^6 kg/hr to supply two additional powerplants (MP-2 and PLES-1). This increase in pumping nearly tripled the tilt rate into the well field. From 1990 to 1994, the north component is fit reasonably well by a linear rate of 99±12 μrad/yr.

In June 1988, the third leveling network was established to provide a more detailed picture of the deformation and consists of 45 monuments within the well-field graben and across the bounding faults. Data from this leveling network show significant changes in the location and magnitude of maximum subsidence in the well field between 1988 and 1994 (figs. 5*A*–*C*). The observed changes probably were caused by a combination of factors and processes including changes in pressure and temperature, infiltration of cold shallow ground water, venting of steam from the reservoir, variations in rock compressibilities, and changes in well locations and injection depths (Sorey and others, 1995). Prior to 1992, the area of maximum subsidence was 500 m east of the production wells that are centered around monument AZ (fig. 5*A*). The offset between the area of maximum reservoir pressure drop at the production wells and the area of maximum subsidence at monument AZ could have been caused by lateral differences in lithology. The production wells are completed in silicified rhyolite of low compressibility. The area around monument AZ, where subsidence is greatest, could be underlain by hydrothermally altered rhyolite, which is highly compressible.

Data collected in 1993 show that the area of maximum subsidence had shifted 500 m west of monument AZ and was centered around the production wells (fig. 5*B*). The change in location and magnitude of maximum subsidence resulted partly from pressure decreases in the production reservoir. A 10-meter decrease in head was caused by a pumping-rate increase to supply the two new powerplants in December 1990. In mid-1991, shallow perforated zones in the injection wells were sealed to prevent thermal breakthrough of the cooled injectate to the production wells and resulted in an additional 15 m of head decline in the production reservoir.

The delay between the pressure drop in the production reservoir in 1991 and the subsidence centered around the production wells in 1993 could

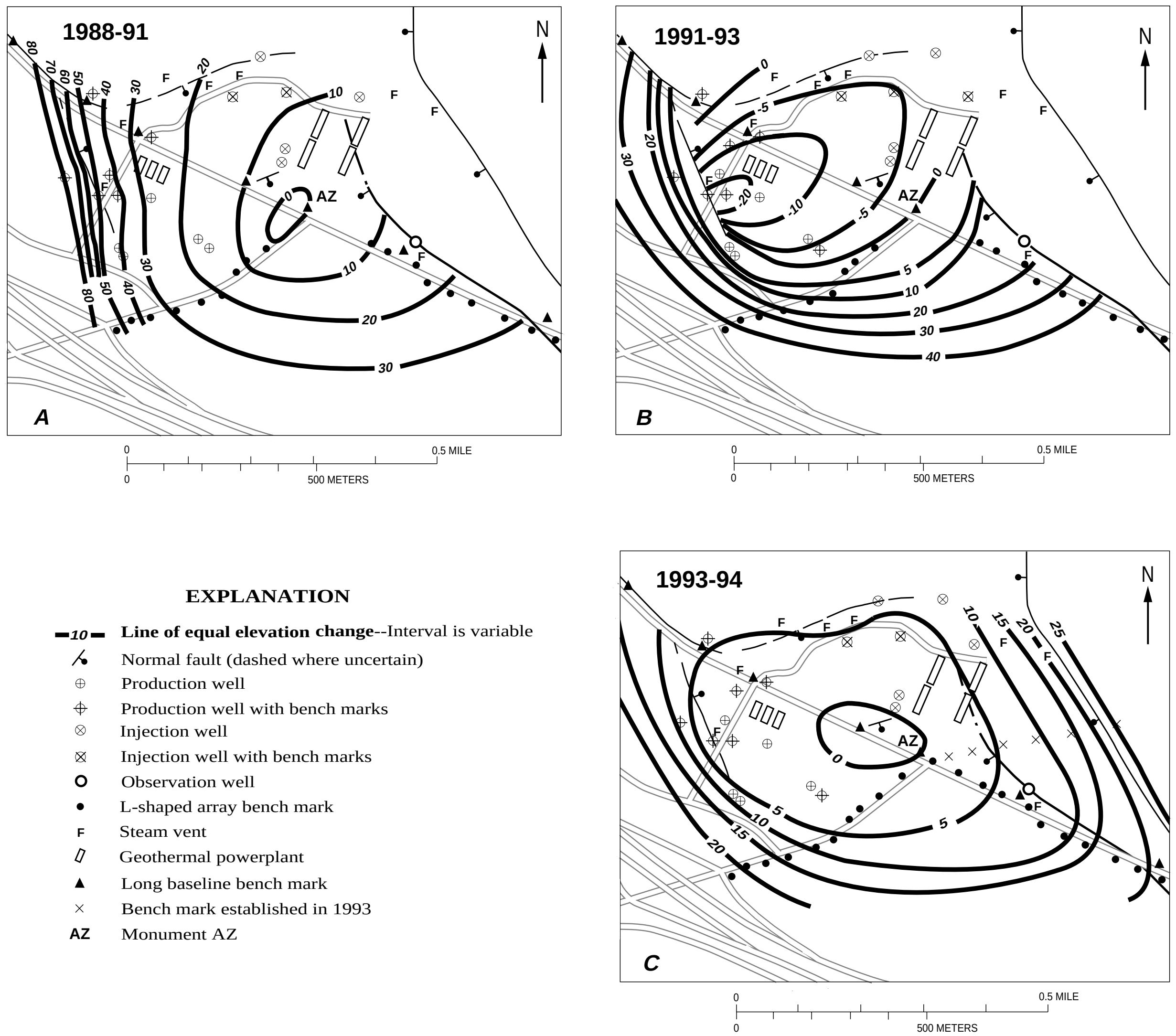

Figure 5. Land-surface elevation change, in millimeters, in the Casa Diablo geothermal well field. *A*, 1988–91. *B*, 1991–93. *C*, 1993–94. Modified from Sorey and others, 1995.

have been caused by thermal expansion of rocks above the production reservoir. A large increase in the volume of steam discharged from fumaroles and along faults was observed during 1991 and most of 1992. The increase in steam discharge was caused by boiling in the reservoir induced by the pressure drop. Thermal expansion was reversed when cold shallow ground water moved toward the pressure low at the production wells.

The data for 1994 show a shift in the area of maximum subsidence towards the center of the graben (fig. 5*C*). The greater degree of isolation between the injection and production reservoirs possibly allowed the pressure drop in the production reservoir to spread across the well field to include the central part of the graben. If very fine-grained materials compose the central part of the graben, the reduction in pore pressure would initiate a slow dewatering process that would propagate from the production wells to the center of the graben. The changes in the location of maximum subsidence between 1993 and 1994 also could be related to changes in the production and injection rates of individual wells in the geothermal field.

REFERENCES CITED

Hill, D.P., Bailey, R.A., and Ryall, A.S., 1985, Active tectonic and magmatic processes beneath Long Valley Caldera, eastern California—An overview: American Geophysical Union, Journal of Geophysical Research, v. 90, no. B13, p. 11,111–11,129.

Langbein, J., 1989, Deformation of the Long Valley Caldera, eastern California, from mid-1983 to mid-1988: American Geophysical Union, Journal of Geophysical Research, v. 94, no. B4, p. 3,833–3,850.

Langbein, J., Hill, D.P., Parker, T.N., and Wilkinson, S.K., 1993, An episode of reinflation of the Long Valley Caldera, eastern California, 1989–1991: American Geophysical Union, Journal of Geophysical Research, v. 98, no. B9, p. 15,851–15,870.

Savage, J.C., Cockerham, R.S., Estrem, J.E., and Moore, L.R., 1987, Deformation near the Long Valley Caldera, eastern California, 1982–1986: American Geophysical Union, Journal of Geophysical Research, v. 92, no. B3, p. 2,721–2,746.

Sorey, M.L., Farrar, C.D., Marshall, G.A., and Howle, J.F., 1995, Effects of geothermal development on deformation in the Long Valley Caldera, eastern California, 1985–1994: American Geophysical Union, Journal of Geophysical Research v. 100, no. B7, p. 12,475–12,486.